Structural design with flowable concrete



Steffen Grünewald[1,2] **Liberato Ferrara[3]** **Frank Dehn[4]**

ABSTRACT

Flowability is a characteristic of concrete with a high workability in the fresh state. In order to achieve flowability the mix design can be considerably different compared to vibrated concrete. Not only the production technique has to be adapted to the higher flowability, but the flow can also cause local differences in material behaviour. With deviating mix design, constitutive laws and provisions related to the structural behaviour established for VC might no longer be applicable. This paper discusses the progress of fib TG 4.3, a Task Group that aims at facilitating the use of innovative flowable materials for the design of concrete structures by providing a state-of-the-art report and recommendations for the structural design with flowable concrete.

Keywords: Flowable concrete, self-compacting concrete, fibres, testing, structural behaviour

1. INTRODUCTION

Concrete technology has been rapidly evolving during the past decades involving sciences as rheology, nanotechnology, waste management, composite materials and others more. Sustainability and durability of concrete structures linked with life cycle analysis are research areas very relevant for society. Effective manufacturing at a high level of quality is an industrial need to remain competitive and to realize the potential concrete has for construction industry. The use of flowable concrete (FC) has many benefits, as it eliminates compaction, eases the realization of aesthetic concrete surfaces, facilitates production and allows developing unique areas for concrete application. In order to successfully produce concrete structures with highly flowable concrete, differences in mix design, production technique and structural design (engineering properties and durability aspects) are possible and have to be considered. These aspects can differ more or less from vibrated concrete (VC),

[1] Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, Netherlands. s.grunewald@tudelft.nl
[2] Magnel Laboratory For Concrete Research, Ghent University, Ghent, Belgium. steffen.grunewald@ugent.be
[3] Department of Civil and Environmental Engineering, Politecnico di Milano, Milano, Italy. liberato.ferrara@polimi.it
[4] Faculty of Chemistry and Mineralogy, Leipzig University, Leipzig, Germany. dehn@mfpa-leipzig.de

depending on the type of concrete. Extending the range of workability of VC, some FC types reported in literature and applied in practice are:

- SCC: Self-compacting concrete (with or without fibres);
- UHPC: Ultra-high performance concrete;
- UHPFRC: Ultra-high performance fibre-reinforced concrete;
- HPFRCC: High performance fibre-reinforced cementitious composites;
- SHCC: Strain-hardening cementitious composites;
- ECC: Engineered cementitious composites;
- FRC: Fibre-reinforced concrete (with a higher flowability).

2. Task Group fib TG 4.3

Task Group fib TG 4.3 focusses on structural design and it considers (Fig. 1a): the influence of mixture composition and characteristics (material), production and related flow phenomena (production) and size, shape and design of structures (structure). The two main aims of fib TG 4.3 are:

- To compile knowledge of different types of FC in a state-of-the art report;
- To provide recommendations on the structural design with FC; the recommendations include different types of FC with a performance-based approach.

fib TG 4.3 defines 'Flowable concrete' as concrete having a slump of at least 200 mm. With a slump of 200 mm compaction still is required; FC not necessarily is self-compacting or self-levelling. For example, by addition of fibres an otherwise self-levelling matrix can have a slump less than 200 mm. FC deviates from VC to the extent that the concrete technologist adjusts the mix design (not only by increasing the dosage of water or superplasticizer): these changes can have implementations related to production and structural design. Model Code 2010 (MC2010) [1,2] includes concrete with a compressive strength up to C120/140; the French UHPFRC-guideline [3] requires a cylinder strength of at least 150 MPa and a minimum ductility to be provided by fibres; the Japanese HPFRCC-guideline [4] focuses on the post-cracking behaviour which is characterised by multiple cracking. In concrete (vibrated and self-compacting concrete) fibre volumes usually do not exceed 1 Vol.-% in applications like floors, slabs and tunnel segments. The areas of expertise are limited so are the guidelines covering those applications. Fig. 1b identifies areas of lack of knowledge and experience.

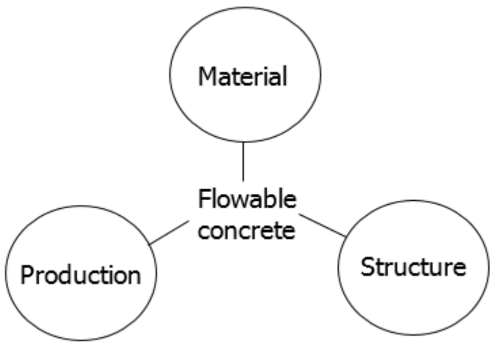

Figure 1a. Flowable concrete, interaction between material, production and structure.

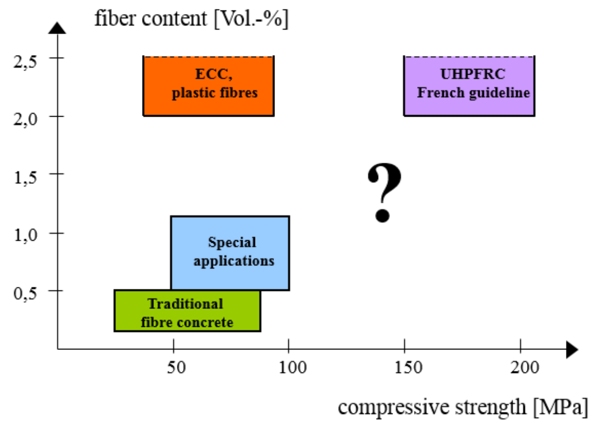

Figure 1b. Areas of experience and knowledge with flowable concrete containing fibres.

fib TG 4.3 aims at developing recommendations for a wider range of mixtures compiling the available knowledge and it collects and analyses research findings from the entire design and production process with FC in order to provide guidance for designers and users of concrete structures built with FC. Besides material-related aspects the focus is also on design-related topics and the structural behaviour of concrete that was cast with a flowable consistency. Table 1 provides an overview of the topics that are covered in the state-of-the-art report of fib TG 4.3.

Table 1. Summary of topics covered by fib TG 4.3.

Chapter in STAR report	**Description**
Flowable concrete	General overview about flowable concrete types
Components and mixture composition	Introduction of mixture constituents and their peculiarities
Fresh state	Influences of mixture constituents and methods to control the rheology
Local effects	Effects of segregation, blocking and fibre orientation on structure
Mechanical characteristics	Hardened state behaviour of flowable concrete types
Creep and shrinkage	Time- and load-dependent behaviour in hardened state
Bond and anchorage	Interactions with other structural components
Durability	Peculiarities of flowable mix design concepts with regard to durability
Production influences/methods	Considerations about casting processes and supply chains
Applications	Examples of structures built with flowable concrete types

fib TG 4.3 interacts with ongoing Task Groups on fibre-reinforced concrete (ACI 544, fib TG 4.1), ultra-high performance fibre-reinforced concrete (fib TG 4.2), performance-based specifications for concrete (fib TG 4.5) and constitutive laws for concrete with supplementary cementitious materials (fib TG 4.6). Several members of fib TG 4.3 joined Technical Committees on mechanical properties of self-compacting concrete (RILEM TCMPS), simulation of concrete flow (RILEM TCSCF) and high performance fibre-reinforced cementitious composites (RILEM TCHFC).

3. CHARACTERISTICS OF FLOWABLE CONCRETE

3.1 Fresh state

Rheological characterisation (i.e. yield stress, viscosity and thixotropy) has been applied to characterize FC. A slump of 200 mm is defined as a minimum for ‘flowable concrete’. A large volume of applied concrete has this workability or is more flowable. However, compaction energy still is required for concrete with a slump of 200 mm. A slump of 200 mm for a concrete density of 2400 kg/m^3 translates in a yield stress of 750 and 904 Pa determined according to references [5] and [6], respectively. Rheological characteristics have implementations on the ease and method of production, formwork pressure, segregation resistance and robustness.

The amount of fibres in concrete is limited since fibres affect the workability. The maximum fibre content depends among others on the paste volume and the maximum size, content, distribution and shape of the aggregates. In addition, the maximum amount of fibres depends on the fibre type; the highest possible (ultimate) fibre dosage is independent from the mixture composition, since the fibres already form a strong network that prevents proper compaction or flow. Stiff fibres (i.e. steel fibres) can form a stable network, whereas thinner and flexible fibres (i.e. polypropylene fibres) form a weaker network that can be more easily agitated with compaction energy. The addition of a higher fibre dosage can cause entanglement and friction between fibres and mainly larger concrete components (coarse aggregates relative to fibre length), which significantly increases the yield stress and the viscosity. Figure 2 shows the effect of steel fibres on the rheological characteristics yield stress and plastic viscosity (reference mixture yield stress of 31 Pa and a plastic viscosity of 81 Pa·s) of a self-compacting concrete (reference slump flow (without fibres): 728 mm). In spite of the pronounced rheological differences compared to the reference SCC, mixtures at the lower fibre dosage per fibre type remained self-compacting [7]. The steel fibres are characterised in Fig. 2 by the aspect ratio (ratio L_f/d_f), the fibre length (L_f) and the fibre dosage.

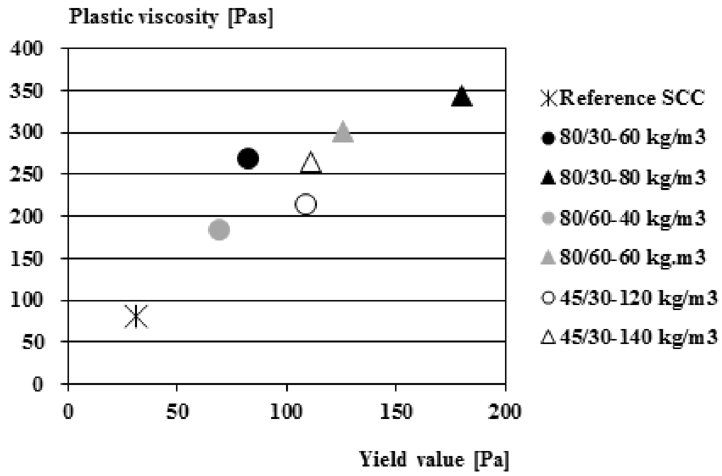

Figure 2. Increase of yield value and plastic viscosity of SCC due to the addition of steel fibres [7].

The consideration of local effects is relatively more important for FC as compared to VC. In some cases the effect is positive, in other cases local effects can have negative consequences, which have to be understood and taken into account, and if possible, counteracted. Examples of local effects are discussed in the following:

- The thixotropic influence of cement paste increases at increasing paste volume in concrete and with the reduction of the water-binder ratio. After the first initial hydration upon contact of cement with water, thixotropic build-up is a major effect observed in FC types; Roussel [8] proposed three thixotrophy classes (Table 2) to distinguish different mix designs for SCC. A_{thix} is a term that adds up to the yield stress equation over the course of time. It is defined as the yield stress τ_0 divided by the flocculation characteristic time T. Thixotropic build-up can cause problems related to the formation of distinct casting layers, incomplete filling, and concrete aesthetics. However, the structural build-up also can have beneficial effects, for example it improves the production efficiency in the case of slip-cast paving [9] or for the production of panels with a flexible mould [10]. When casting self–levelling concrete that rapidly builds up strength, the formwork pressure drops quickly.

Table 2. SCC thixotropy classification [8].

SCC type	**Flocculation rate A_{thix} (Pa/s)**
Non-thixotropic SCC	Less than 0.1
Thixotropic SCC	Between 0.1 and 0.5
Highly thixotropic SCC	Higher than 0.5

- Robustness of self-compacting concrete is important since compaction energy is not available for the production. The robustness against temperature-induced performance variations of concrete types incorporating high amounts of polycarboxylate ether based superplasticisers (PCE) can be strongly influenced by the modification of the PCE and the mixture composition [11]. The reason is that PCE interacts with the hydration phases of the reactive components in the binder paste, which induces a time-dependent effect. It was found that low powder SCCs are more prone to deviation in rheological properties than powder rich SCCs at low temperatures. At low temperatures (<< 20°C) the binder cannot produce sufficient new hydration phases, which would attract PCE to stabilise the flow. However, the use of high charge density PCE as usually used in pre-cast concrete could compensate for these negative effects. At high temperatures, the situation was found to be exactly inverted. SCC with low powder content may be more robust against influences induced by PCE than powder rich SCC, since a powder rich SCC tends to rapid stiffening due to the dense particle packing, which is aggravated by the temperature-accelerated hydration. This high temperature effect can be compensated by using low charge density PCE, which is adsorbed over a longer period of time than high charge density PCE. Table 3 provides an overview of which types of SCC are more prone to failure in a particular climate.

Table 3. Examples of influencing factors on the robustness of SCC against temperature influences [12].

		Charge density of PCE		Problem field	Solution
		low	**high**		
Stabilising agent type	5 °C	poor flow, low strength	good flow retention	PCE dependency	High charge density PCE
	20 °C	Good flow retention	Good flow retention	-	-
	30 °C	Good flow retention	Medium flow retention	-	-
Powder type	5 °C	Good flow retention	Good flow retention	-	-
	20 °C	Good flow retention	Medium flow retention	-	-
	30 °C	Good flow retention	Poor flow retention, low strength	PCE dependency	Low charge density PCE

Like thixotropy, robustness is a specific material characteristic of FC and SCC. Compaction energy can compensate to some degree for a deviation in mixture characteristics in the fresh state for VC, which is a step towards production robustness. Robustness at the material level is most relevant for SCC. Three robustness classes (Table 4) according to its performance in slump flow, sieve segregation resistance test, and L-box ratio were proposed in [13]. The robustness class is determined by testing the fresh concrete properties with water content variations (± 10 kg/m^3) from the reference water content and observing the performance change (unit: performance change divided by water dosage change). The larger the change at a given water dosage, the higher is the robustness class of the SCC (C1-C3). This method can help specifying and assessing mixture compositions in terms of their robustness with regard to variations in the total water content; in some cases viscosity-modifying admixtures are recommended to enhance the robustness.

Table 4. Robustness classes: response change per water variation [13].

Test method	**Unit**	**Robustness class** C1	C2	C3
Slump flow	[mm/l]	< 6.2	6.2 to 10.0	> 10.0
Sieve stability	[%/l]	< 0.62	0.62 to 1.0	> 1.0
L-box ratio	[-/l]	< 0.012	0.012 to 0.02	> 0.02

- The rheological behaviour is shear stress-dependent; the particle shape can cause preferred orientation during the flow.

An example of the former aspect is reported by Spangenberg et al. [14]. Rheological characteristics like yield stress and viscosity are shear rate-dependent. Shear- and gravity-induced migration of particles can lead to local differences in concentrations. The distribution of coarse aggregates was studied (depending on the distance from the casting point and the vertical position) in beams cast with SCC (dimensions of beams: L=4.0 m/H=0.3 m/W=0.2 m). Different coarse aggregate concentrations were observed over the height of the beam. At the highest point no segregation was observed. However, at a height of about 120 mm above the bottom, the concentration was lower compared to other areas of the beam. According to the authors, differences in shear rate and stress cause rheological differences of the concrete, which promotes the migration of particles in a specific zone. The migration of particles increases the yield stress and viscosity in the lower layer until a state of balance is obtained. Simulations indicated that the highest shear rate was obtained at a height of 50-100 mm above the bottom of the mould.

Fibre orientation is an example of both aspects: shear stress- and shape-dependency. Fibres are long elongated particle that will rotate until the lowest energy level position is reached. Driving forces for orientation are (due to higher shear stresses): 1) walls, 2) reinforcement bars, 3) casting areas and 4) free-flow (not parallel) concrete casting front. Flow conditions can be distinguished in free-flow condition (extensional stress-induced orientation) [15] and flow along walls (shear-induced orientation) [16]. Due to the flow of concrete (either flow caused by its own weight or i.e. flow that is caused by adding vibration energy with i.e. an external vibrator) fibres are free to rotate if this is not counteracted by 1) a network of fibres, 2) a high yield stress and/or plastic viscosity, 3) the presence of other particles in concrete and 4) walls. The orientation of fibres is further discussed in Section 4.

3.2 Hardened state

The mixture composition of some types of FC does not differ much compared to VC. However, the higher the flowability, the higher the compressive strength and the more fibres a mixture contains the larger are the expected differences in mix design and related characteristics in the hardened state. With

- a higher content of fine particles,
- a lower water-binder ratio,
- a larger fibre contribution to the tensile strength and ductility,

even more pronounced differences can be observed in the hardened state properties. In the following two characteristics are discussed in more detail: modulus of elasticity and time-dependent behaviour.

Modulus of Elasticity

Because of the wide range of mixture compositions and aggregate characteristics, the modulus of elasticity is expected to vary in a wider range than for VC at a given compressive strength. Figure 3 compares provisions given in MC2010 [1], the German DAfStb-document on UHPFRC [17] and the Japanese HPFRCC-guideline [4]; Table 5 shows the provisions. The applicable range of compressive strength is limited in MC2010 to a maximum of C120/140 (cylinder compressive strength of 120 MPa). Considering Quartzite as a common aggregate type in concrete, the modulus of elasticity of UHPFRC (coarse grain [17]) is following this trend quite well. The provision for concrete with basalt aggregates, especially for very high strength classes, significantly overestimates the actual modulus of elasticity; such high values were never found in UHPC. The formula for E_{ci} in MC2010 presumes a certain volume percentage of coarse aggregates. One reason for an overestimation of the modulus of elasticity with basalt is, that such high volumes (60-70%) will not be applied in UHPC. On the other hand, HPFRCC can have a modulus of elasticity comparable with lightweight concrete or normal weight concrete containing sandstone aggregates (Fig. 3).

Table 5. Equations to calculate the modulus of elasticity with reference.

Equation	To be used for	Reference
$E_{ci} = E_{c0} \cdot \alpha_E \cdot \left(\frac{f_{ck} + \Delta f}{10} \right)^{1/3}$	Basalt, dense limestone aggregates, αE=1.2 Quartzite aggregates, αE=1.0 Limestone aggregates, αE=0.9 Sandstone aggregates, αE=0.7	[1]
$E_{HPFRCC} = 1.77 \cdot 10^4 \cdot \sqrt{\frac{\gamma}{18.5}} \cdot \left(\frac{f'_{ck}}{60} \right)^{1/3}$		[4]
$E_C = 9500 \cdot fc^{1/3}$	Coarse grain UHPFRC	[17]
$E_C = 8800 \cdot fc^{1/3}$	Fine grain UHPFRC	[17]

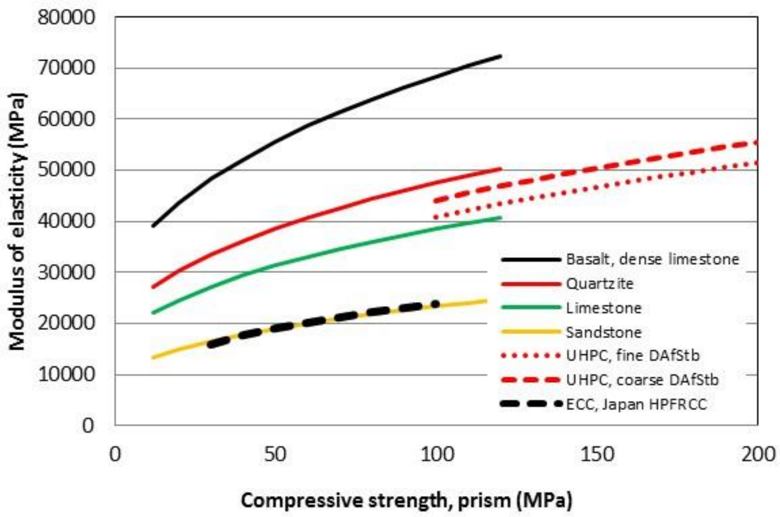

Figure 3. Comparison of the theoretical modulus of elasticity according to three recommendations Model Code 2010 [1], DAfStb UHFB [17] and Japanese HPFRCC–guideline [4].

Time- and load-dependent behaviour

At specific locations in a structure, strain caused by shrinkage and creep may add up or creep may lead to relaxation and it reduces the stress caused by shrinkage strain. Because of different mixture compositions the 'laws' which are valid for shrinkage and creep of VC have to be carefully checked if they can be applied to these new types of concrete. A detailed discussion of the time- and load-dependent behaviour for FC can be found in [18].

Creep: Even when results of different studies are not consistent, there seems to be a general agreement that the creep coefficient and the specific creep are normally slightly higher for SCC compared to VC [19]. Specific creep of Ultra High Performance Concrete (UHPC) is in the range of 0.01-0.035 ‰/MPa, while the creep coefficient is in the range of 0.5-1.2 [20]. Because of a high paste volume ECC (HPFRCC) shows large creep deformations, but due to a low E-modulus creep coefficients can be even smaller than the ones of VC [4].

Autogenous shrinkage: Influence of paste volume: At a constant w/p, the autogenous shrinkage of SCC increases with increasing paste volume [21]. As a result, VC shrinks less than SCC when the binder composition and strength class are the same. Autogenous shrinkage of UHPC is considerably larger than the one of VC [22]. In ECC a decrease in paste volume by the addition of fine-grained aggregates (grain size of 0.15-0.30 mm) can significantly reduce autogenous shrinkage [23].

Drying shrinkage: The total shrinkage increases with increasing paste volume [19]. When w/p is kept constant, the relation between shrinkage and paste volume is approximately linear and can be regarded as the dominating parameter in drying shrinkage. Drying shrinkage in UHPC is very low (in the range of 0.1‰) compared to autogenous shrinkage [24]. Although the shrinkage of ECC is high (range of 1‰ at a RH of 60%), its tensile strain capacity seems to be higher than the drying shrinkage deformation [25].

Cracking sensitivity: The proneness to cracking of a particular concrete is not only determined by the shrinkage strain but also by the interaction of the time-dependent viscoelastic properties, the tensile strength and the E-modulus. When the w/p is constant and the tensile strength is similar, the tensile stress of SCC developing in the ring test and in a shrinkage frame with passive restraint increases with paste volume [19,21]. The time of cracking follows the same pattern. The relaxation of VC and SCC having a considerable higher paste volume differs; VC shows a lower degree of relaxation, which is the result of the generally lower creep of VC. UHPC reaches higher stress levels than VC and SCC before it cracks in the ring test and in case of additional fibre reinforcement no cracking occurred. Shrinkage-induced cracking of UHPC is a special case as the high fibre content leads to a ductile behaviour.

4. FROM MATERIAL CHARACTERISATION TO STRUCTURAL BEHAVIOUR

4.1 Material qualification

The bending test (3- or 4-point) has been widely applied and accepted as a method for the characterization of the fibre contribution in tension, although it is not a direct tensile test. An example is the three-point bending test according to EN 14561 [26]. Accepted test methods also have to be available to quantify the behaviour of FRC as a function of fibre orientation. For quality control during production such test methods are in development; examples for non-destructive test methods are magnetic inductance [27] and X-ray tomography [28]. Recently, tests on cube/tile specimens were proposed (destructive and non-destructive) that allow for the qualification in three different directions (i.e. Multidirectional Double-Punch Test [29] and the Double Edge Wedge-Spitting Test [30] taking into account the effect of both the distribution and the orientation of fibres. Herein, mainly steel fibres were considered and tested. The transfer of experimental results of small test specimens to larger structures (Fig. 4) has to be performed with care. The focus should be on the prescription concerning manufacturing and representativeness of the obtained orientation with respect to the intended application.

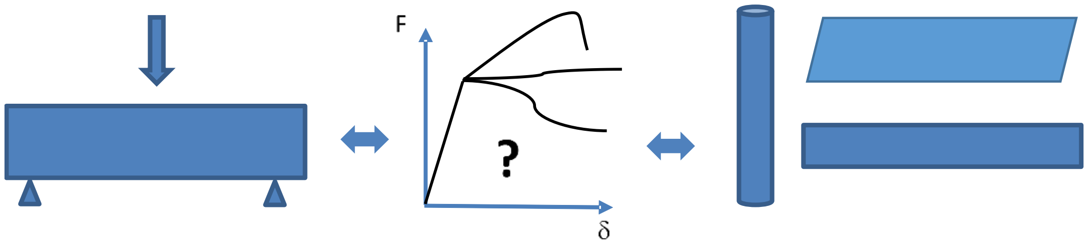

Figure 4. Translation of results of test specimens to the performance of full-scale structures.

K-concept Model Code 2010

The K-concept has been introduced in MC2010 [1] for fibre-reinforced concrete (Eqs (1) and (2)), and also has been successfully applied for UHPFRC since the publication of the first French recommendation of this concrete type in 2002. The K-factor takes into account production-, workability- and structure-related influences on the performance of concrete structures reinforced with fibres. The implementation of the K-factor concept in MC2010 opens doors for future design recommendations.

$$f_{F_{tsd,\mathrm{mod}}} = f_{F_{tsd}} / K \tag{1}$$

$$f_{F_{tud,\mathrm{mod}}} = f_{F_{ud}} / K \tag{2}$$

Design values in the tensile zone determined from the bending tests have to be adjusted with: K > 1 fibre orientation being unfavourable or K < 1 fibre orientation being favourable (relative to the small test specimen performance). How to determine K is not specified and also depends on the type of structure. For structural design the application of the K-factor concept means that a reduction or an increase of the post-cracking strength of fibre concrete is possible which has to be determined experimentally. Ferrara et al. [31] studied the relation between the residual strength and fibre orientation for bending, wedge splitting and direct tensile tests. In each case they obtained a linear relation for post-cracking strength and number of fibres in a cross-section. Such relation depends on the combination of fibre type, applied concrete mixture and its characteristics in the hardened state. In their study, the range of K-factors was between 0.4 (favourable) and 2.0 (unfavourable). Establishing such relationships allow predicting the structural behaviour based on the actual fibre orientation in a structure.

Design considerations

MC2010 allows carrying out flexural design by assuming a residual stress block in tension. The input for the calculation is obtained from testing of prisms. The residual stress values are specified concerning crack width, variation of test results, safety factors and maximum strain to be taken into account. Besides for flexural design, MC2010 also includes provisions related to shear and shear punching; the resistance of the concrete structure is the sum of contributions of the concrete and reinforcement. Dependent on the size of the structure and possible redistribution effects other factors might be applicable, which are not specific for fibre concrete. The K-factor concept is discussed in Section 4.2 with regard to the French UHPFRC-recommendation, Danish and German guidelines for fibre-reinforced concrete structures.

4.2 Design guidelines for fibre-reinforced concrete

This section discusses three guidelines for fibre-reinforced concrete, which are: French UHPFRC-guideline [3], Danish design guideline [32] and German DAfStb guideline [33].

All guidelines have in common that they are more or less able to take into account the anisotropy of fibre concrete, which means in practice that a structure can have a higher or a lower performance compared to what is expected from the results of material tests like the bending test. For details concerning the described provisions and structural design the reference guidelines should be consulted. Table 6 compares different design aspects of the four guidelines for fibre-reinforced concrete.

Table 6. Comparison of design aspects of the four discussed design guidelines.

Aspect	**French AFGC**	**Model Code 2010**	**German DAfStb**	**Danish guideline**
Applicable for concrete strength	≥ 150 MPa (cylinder)	≤ 120MPa (cylinder)	≤ C50/60	≤ C50/60
Self-compacting concrete	Yes	Yes	No	Yes
Fibre concrete characterization	3-/4-point bending	3-point bending (EN 14651)	4-point bending	3-point bending (DS EN 14651)
Tensile behaviour	Residual strength block	Residual strength block	Residual strength block	Residual strength block
Relevant CMOD-values	Depend on fibre/ characteristic lengths	0.5 mm (SLS), $w_u \leq 2.5$ mm (ULS)	0.5 mm (SLS), 3.5 mm (ULS)	0.5 mm (SLS), 3.5 mm (ULS)
Shear provision	X	X	X	X
Shear punching provision	X	X	X	X
Concept for local fibre orientation	Yes	Yes	No	Yes
Specific fibre orientation values per structure	-	-	X (0,5/1,0 for defined applications)	X (not all cases are included)
Full/larger scale verification required for orientation numbers	X	X	Orientation factors are proposed	Experimental verification or simulation

French UHPFRC-guideline

In France, already the second edition of the guideline for UHPFRC has been published [3]. As it was the first guideline on UHPFRC worldwide, it also introduced a helpful design concept that includes fibre orientation. The K-factor validates design assumptions as a result of tests on parts of full-scale test elements. By measuring the maximum bending moment of cast and cut specimens, their ratios can be determined for local (most unfavourable and relevant for a specific position) and global design (Table 7). K-factors higher than 1 (1/K is applied as a correction) indicate structural performance lower than the reference (cast) specimens and are therefore unfavourable. The K-factor concept only considers the post-cracking part of the bending response.

Table 7. Definition of local and global parameters of the French K-factor design concept.

Global value	Local value
K_{global} concerns the overall structural behaviour corresponding to stresses, which require fibre resistance in larger areas and which are not affected by a local defect (for example shear or the bending strength of a slab).	K_{local} corresponds to local stresses, which require good fibre resistance in very local areas (i.e. prestressing distribution).
$K_{global} = \dfrac{M_{cast,average}}{M_{cut,average}}$	$K_{local} = \dfrac{M_{cast,average}}{M_{cut,\min/\max}}$

Simon et al. [34] discussed the robustness and reliability of the K-factor concept with reference to case-studies. The French UHPFRC-recommendation proposes as a first design approximation 1.75 for local effects and 1.25 for global effects. In several cases, K-factors lower than 1 were found, which is considered the minimum design value. In such cases, the performance of a part of a full-scale element was better than the experimental results of laboratory specimens. In case of the Pont Du Diable-footbridge the highest obtained local K-factor was 2.12.

Besides provisions for bending and shear, shear punching is also included in the French guideline. The tensile behaviour is taken into account and the K-factor relates the performance of small specimens with the performance of a structure.

Danish design guideline

The Danish guideline [31] contains parts specifically addressing self-compacting concrete reinforced with fibres. In order to support the guideline, a project was executed on fibre-reinforced SCC; important conclusions of this project were summarised by Thrane et al. [35]. Concerning the understanding of fibre orientation and its relation with structural performance, the Danish guideline is the most advanced among the four discussed recommendations in this chapter. Orientation numbers are proposed for fibre-reinforced SCC, which depend on:

- Geometry of the structural member;
- Type of reinforcement (steel fibres only or combined reinforcement);
- Concrete type and rheological characteristics;
- Casting conditions.

As was observed among others by Ferrara et al. [31] and Thrane et al. [35], the residual tensile strength (tensile strength after cracking) depends on the orientation number, which can be determined with Eq (3). α_0 usually is determined by counting fibres in a cross-section, which also includes differences in distribution as well as orientation of the fibres.

$$N_f = \frac{V_f}{\pi \cdot r_f^{\,2}} \cdot \alpha_0 \tag{3}$$

with: N_f Number of fibres
V_f Volume of fibres
r_f Fibre radius
α_0 Fibre orientation (1: 1D; 0.5: 3D; 0.64: 2D; 0: 1D/2D parallel to fibre plane)

The local fibre orientation can be determined by:

- Casting (numerical) simulations;
- Trial casting with sampling and fibre counting;
- Experience (data is already available from earlier project(s)).

With one of the following methods the amount of fibres in a cross-section can be determined: visual inspection of cutting planes, computer tomography (CT) scanning and/or casting simulations. A structural verification can be performed with fibre counting from core samples taken from the structural member. With the fibre orientation approach, the residual tensile strength can be determined with regard to the expected condition with test specimens and transferred to a structural performance. Such translation from test specimen orientation number ($\alpha_{o,ref}$) to orientation number in a structure (α_o) is implemented in the Danish guideline. This approach yields Eq (4) for the residual tensile strength f_{ct0}^{f} (α: fibre orientation; κ: fibre orientation factor), which includes experimental values from bending tests.

$$f_{ct0}^{f} = \frac{\alpha_0}{\alpha_{0,ref}} \cdot f_{cto,ref}^{f} = \kappa_F^f \cdot f_{cto,ref}^{f} \tag{4}$$

Thrane et al. [35] found that the average fibre orientation in small beams (prisms for flexural testing) was 0.60 for VC and 0.78 for SCC containing fibres; in the Danish guideline 0.84 is recommended for SCC [32]. These are the reference (test specimen) orientation numbers $\alpha_{0,ref}$ with which orientation numbers determined in a structure need to be converted (Eq 4). Similar orientation numbers (±0.78; Orientation number (L_f in mm) = $0.698+0.00177 \cdot L_f$) were obtained with image analysis for SCC containing steel fibres [36]. Assuming the effect of walls on fibre orientation within an area having the width of a fibre length (test specimen: $150 \cdot 150 \cdot 600$ mm^3), fibre orientation numbers of 0.69 and 0.865 are obtained for the bulk and the affected area within a fibre length, respectively. Correction factors applied in the Danish guideline are summarised in Table 8.

Table 8. Correction factors for the residual stress (applicable for VC and SCC).

Adjustment for	Correction factor
Influence of the member size on the coefficient of variation	$\kappa_G^f = 1.0 + A_{ct}^f \cdot 0.5 \leq 1.70$
Influence of fibre orientation	**Slump concrete:** General: $\kappa_F^f = 0.5$ Plane structures cast in horizontal position (width > 5 times height) for flexural and tensile loading $\kappa_F^f = 1.0$ **Self-compacting concrete:** Danish guideline proposes value in an appendix, not every direction and/or loading situation is included

The Danish guideline allows designing structural elements in bending, for shear and shear punching; fibres can be taken into account for crack width considerations. Design limitations can be found with regard to minimum reinforcement, design approach and assumptions. Additional investigations are required to verify design assumptions for prestressed members and structures. Fibre orientation factors for SCC are proposed in the Danish guideline for beams, solid slabs, walls, columns and foundations; for other cases/directions they have to be determined.

German DAfStb guideline

The German DAfStb guideline [33] was used as the basic document for the preparation of the Danish guideline. It consists of three parts, which are 1) design and construction, 2) specification, performance, production and conformity and 3) execution. Design in bending, shear, torsion, shear punching are considered and, crack width and deformation provisions are included. The German guideline does not cover: prestressed concrete, lightweight concrete, concrete with strengths higher than or equal to C55/67, self-compacting concrete, sprayed concrete, steel fibre concrete in exposition classes XS2, XD2, XS3 and XD3, when combined with rebars. In the German guideline, κ_F^f is not directly related to the orientation number, but has to be chosen according to Table 9.

Table 9. Correction factors of residual tensile stresses for VC in the German DAfStb-guideline.

Adjustment of	Correction factor
Influence of the member size on the coefficient of variation	This parameter takes into account the effect of the size of the structure on the variation of tensile performance $\kappa_G^f = 1.0 + A_{ct}^f \cdot 0.5 \leq 1.70$
Influence of fibre orientation	This factor takes into account the fibre orientation $\kappa_F^f = 0.5$ For thin, horizontally produced elements (b>5h) $\kappa_F^f = 1.0$ For beams in direction of the longest side for flexural and tensile loading

5. CONCLUSIONS

The use of flowable concrete is a step towards production efficiency and enhancement of the quality of concrete structures as well as towards a more efficient structural use of the material performances. The understanding of the behaviour of flowable concrete has been significantly improved during the past years. Simulations on the development of microstructure, degradation mechanisms, fracture mechanics and flow behaviour are possible and test methods have been developed to assess the behaviour on the material level, during production and in the structure. Due to the variety of components applied and the wide range of design criteria, performance-based specifications are required. With sometimes large deviations in mix design a good understanding of the overall behaviour of flowable concrete is a necessity covering material, production and structural behaviour.

ACKNOWLEDGEMENTS

Contributions to the work of the fib Task Group 4.3 were made by J. Barros, M. Behloul, H. Beitzel, G. Bertram, P. Billberg, F. Dehn, P. Domone, L. Ferrara, B. Freytag, R. Gettu, T.A. Hammer, T. Kanstad, F. Laranjeira, L. Martinie, S. Nunes, M. di Prisco, Y. Sato, W. Schmidt, M. Sonebi, P. Stähli, H. Stang, J. den Uijl, L. Vandewalle, J.C. Walraven, K. Zilch, J. Spangenberg, A. Leemann, B. Obladen, S. Taylor, N. Roussel, M. Geiker, B. Barragan, J. Cairns, G. Fischer, S. Grünewald.

REFERENCES

[1] fib bulletin 65 (2012). Model Code 2010, Final draft, Volume 1, federation international du béton (fib), Lausanne, Switzerland, ISBN: 978-2-88394-105-2.

[2] fib bulletin 66 (2012). Model Code 2010, Final draft, Volume 2, federation international du béton (fib), Lausanne, Switzerland, ISBN: 978-2-88394-106-9.

[3] AFGC (2013). UHPFRC, Recommendations, AFGC Groupe de travail BFUP.

[4] JSCE HPFRCC (2008). Recommendations for Design and Construction of High Performance Fiber Reinforced Cement Composites with Multiple Fines Cracks (HPFRCC), Concrete Engineering Series 82, Japan Society of Civil Engineers, 2008.

[5] Roussel, N. (2006). Correlation between yield stress and slump: Comparison between numerical simulations and concrete rheometer results, *Materials and Structures*, 39, pp. 501-509.

[6] Hu, C. [*et al.*] (1996). Validation of BTRHEOM, the new rheometer for soft-to-fluid concrete, *Materials and Structures*, 29(194), pp. 620-631.

[7] Grünewald, S. (2012). Fibre reinforcement and the rheology of concrete. In: Roussel, N. (Ed.), Understanding the rheology of concrete, Cambridge: Woodhead Publishing Limited. pp. 229-256.

[8] Roussel, N. (2006). A thixotropy model for fresh fluid concretes, Theory, validation and applications, *Cement and Concrete Research* 36(10), pp. 1797-1806.

[9] Shah, S.P. [*et al.*] (2007). Research on SCC: Some emerging themes, *5th Int. RILEM Symposium on Self-Compacting Concrete (SCC 2007)*, Ghent, Belgium, pp. 3-14.

[10] Schipper, H. R. [*et al.*] (2014). Optimization of the flexible mould process for the production of double-curved concrete elements, *1st Concrete Innovation Conference*, Oslo, Norway.

[11] Schmidt, W. (2014). Design Concepts for the Robustness Improvement of Self-Compacting Concrete - Effects of Admixtures and Mixture Components on the Rheology and Early Hydration at Varying Temperatures. PhD thesis, Eindhoven University of Technology.

[12] Schmidt, W. [*et al.*] (2013). Optimierung der Robustheit von selbstverdichtendem Beton, *Beton- und Stahlbetonbau*, 108(1), pp. 13-21.

[13] Grünewald, S.; Walraven, J.C. (2009). The optimisation of self-compacting concrete with viscosity agents, *17th Internationale Baustofftagung*, Weimar, Germany, pp. 1/1191-1/1196.

[14] Spangenberg, J. [*et al.*] (2012). Patterns of gravity induced aggregate migration during casting of fluid concretes, *Cement and Concrete Research*, 42, pp. 1571-1578.

[15] Thrane, L.N. [*et al.*] (2013*).* Guideline for execution of steel fibre reinforced SCC, Danish Technological Institute, Printing, Paritas A/S, Taastrup / Denmark, ISBN: 978-87996246-1-4.

[16] Martinie, L.; Roussel, N. (2011). Simple tools for fiber orientation prediction in industrial practice, *Cement and Concrete Research*, 41, pp. 993-1000.

[17] DAfStb UHFB (2008). Sachstandsbericht Ultrahochfester Beton, Deutscher Ausschuss für Stahlbeton, Beuth Verlag, Berlin, ISBN: 3-410-65045-4, 2008 (in German).

[18] Leemann, A. [*et al.*] (2015). Time- and load-dependent behaviour of flowable concrete: progress report of fib Task Group 4.3, *Proceedings fib Symposium Copenhagen – Concrete Innovation and Design*, to be published.

[19] Leemann, A.; Lura, P.; Loser, R. (2011). Shrinkage and creep of SCC - the influence of paste volume and binder composition. *Construction and Building Materials*, Vol. 25, pp. 2283-2289.

[20] Flietstra, J. [*et al.*] (2012). Creep behaviour of UHPC under compressive loading with varying curing regimes. *3rd International Symposium on Ultra-High Performance Concrete*, Kassel,

Germany, pp. 333-340.

[21] Rozière, E. [*et al.*] (2007). Influence of paste volume on shrinkage cracking and fracture properties of self-compacting concrete. *Cement and Concrete Composites*, Vol. 29, pp. 626-636.

[22] Loukili, A.; Khelidj, A.; Richard P. (1999). Hydration Kinetics, Change of Relative Humidity, and Autogenous Shrinkage of Ultra-High-Strength Concrete. *Cement and Concrete Research*, Vol. 29, pp. 577-584.

[23] Billington, S.L.; Rouse, J.M. (2003). Time-dependent response of highly ductile fiber-reinforced cement-based composites. *Proceedings of the International Symposium of "brittle Matrix Composites"*, Warsaw, Poland, pp. 47-54.

[24] Koh, K. [*et al.*] (2011). Shrinkage properties of ultra-high performance concrete. *Advanced Science Letters*, Vol. 4, pp. 948-952.

[25] Weimann, M.B.; Li, V.C. (2003). Hygral behavior of engineered cementitious composites (ECC). *International Journal for Restoration of Buildings and Monuments*, Vol. 9, pp. 513-534.

[26] EN 14651 (2005). Test method for metallic fibered concrete – Measuring the flexural tensile strength (limit of proportionality (LOP), residual).

[27] Ferrara, L. [*et al.*] (2012). Non-destructive monitoring of fiber dispersion in fiber reinforced concrete: A comparison between different methods, *Proceedings BEFIB 2012 – Fibre reinforced concrete: challenges and opportunities*, Barros, J. et al. (Eds.), ISBN: 978-2-35158-132-2, pp. 1444-1456.

[28] Suuronen, J.P. [*et al.*] (2013). Analysis of short fibres orientation in steel fibre-reinforced concrete (SFRC) by X-ray tomography, Materials and Structures, February 2013, V48 (3), pp. 1358-1367.

[29] Blanco Álvarez, A. (2013). Characterization and modelling of SFRC elements, PhD thesis, Universitat Politècnica de Catalunya, Barcelona.

[30] di Prisco, M.; Ferrara, L.; Lamperti, M. (2013). Double edge wedge splitting (DEWS): an indirect tension test to identify post-behaviour of fibre reinforced cementitious composites, *Materials and Structures*, DOI 10.1617/s11527-013-0028-2.

[31] Ferrara, L., [*et al.*] (2012). Identification of tensile behaviour of SFR-SCC: Direct VS. indirect tests, *Proceedings BEFIB 2012 – Fibre reinforced concrete: challenges and opportunities*, Barros, J. et al. (Eds.), ISBN: 978-2-35158-132-2, pp. 83-84 & CD.

[32] Kasper, T. [et al.] (2014). Design guideline for structural applications of steel fibre reinforced concrete, SFRC consortium, Denmark.

[33] DAfStb (2012). DAfStb-Richtlinie: Stahlfaserbeton, Deutscher Ausschuss für Stahlbeton, Berlin, Entwurf November 2012. (in German).

[34] Simon, A., Corvez, D., Marchand, P. (2013). Feedback of a ten years assessment of fibre distribution using K factor concept, *Int. Symposium on UHPFRC, Designing and Building with UHPFRC: from innovation to large-scale realizations*, RILEM Publications S.A.R.L., Bagneux, ISBN: 978-2-35158-130-8, pp. 669-678.

[35] Thrane, L.N. [*et al.*] (2013). Guideline for execution of steel fibre reinforced SCC, Danish Technological Institute, Printing, Paritas A/S, Taastrup / Denmark, ISBN: 978-87996246-1-4.

[36] Grünewald, S. (2004). Performance-based design of self-compacting fibre reinforced concrete, PhD thesis, Delft University of Technology, ISBN: 9040724873.